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## Carbon nanotubes grown on glass fiber as a strain sensor for real time structural health monitoring

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In order to more effectively monitor the health of composite structures, a fuzzy fiber sensor has been developed. The fuzzy fiber is a bundle of glass fibers with carbon nanotubes or nanofibers (CNTs or CNFs) grown on the surface. The nanotube coating makes the fiber bundle conductive while the small conductive path increases sensitivity. The fuzzy fiber sensor can replace conventional metal foil strain gauges in composite applications. The electrical response of the sensor is monitored in real time to measure strain, vibration, cracking and delamination. Continuous monitoring provides instant notification of any problems. Implementation of this sensor network in a composite can increase service life, decrease maintenance costs and greatly reduce inspection downtime.

**Keywords:** carbon nanotube; sensor; polymer composite; structural health monitoring

### 1. Introduction

The current push toward composite structures of increasing complexity has led to an increased need for structural health monitoring (SHM) systems. Proper SHM methods provide an indication of the condition of the structure so that inspection costs and downtime can be reduced and service life can be increased. These systems must be easily integrated into the composite structure in order to be of the most use. Current SHM approaches often use strain gages, optical fibers, accelerometers and, more recently, piezoelectric sensors. These sensors provide data at specific points and therefore must be placed in the correct locations to detect the desired event. Algorithms have been developed to triangulate the location of damage based on the response of nearby sensors [1,2]; however, this method is not ideal. Additionally, these sensor technologies are difficult to imbed in a composite structure and may not be compatible with the local geometry requirements.

Investigation into the sensing applications for carbon nanotubes (CNTs) and nanofibres (CNFs) is rapidly increasing. CNT- and CNF-based sensors have been found to have outstanding ability to mediate fast electron transfer for a wide range of electroactive species, enhance electrochemical reactivity, accumulate important biomolecules and alleviate surface fouling of electrodes [3–5]. Strain and bending of CNTs may cause reproducible changes in their conductance, making it possible to construct electromechanical

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sensors [6,7]. The piezoresistance properties of CNTs in polymeric composites are being investigated for smart structure applications [8–9].

One approach to wide-area damage detection is to harness the ability of certain classes of materials to provide a self-diagnosing function. Schulte's group has reported that measuring changes in electrical resistance of carbon fiber-reinforced plastic composites during tensile and fatigue loading can be used as a nondestructive evaluation technique [10,11]. The same idea was used to detect the water leakage in reinforced concrete, in which the cement mortar conductivity decreased with decreasing water content and leakage [12]. The proposed effort seeks to harness the inherent conductivity of CNTs to provide for *in-situ* sensing of structural damage [13].

There are a number of other CNT sensors under study that may have working principles completely or partially different from the above sensors. For example, based on the change of mechanical resonant frequency of CNTs due to variation of temperature, pressure, mass and strain, the corresponding thermal sensors, pressure sensors, mass sensors and strain sensors were suggested [14]. They also have large length-to-diameter aspect ratios that can provide high surface area for depositing external materials or performing functionalization for electrodes used for a variety of applications. This study sought to develop a CNT-based sensing technology which could provide wide area detection and be easily integrated into a composite structure.

## 2. Material fabrication

Electrodes were fabricated using glass fiber with CNTs uniformly attached by low-cost thermal chemical vapor deposition (CVD). The parameters of the CVD can be altered to change the density and length of the CNTs. Figure 1 shows an SEM micrograph of a CNT fuzzy fiber with low density, relatively short CNTs, compared to Figure 2, which shows a CNT fuzzy fiber with a longer, high density CNT coating. The two configurations were tested separately to determine which one would provide the best response to mechanical stimulus. The sensing element, composed of a plurality of fuzzy fibers, can be monitored in a similar fashion to a conventional metal foil strain gauge. The electrical resistivity of the fuzzy fiber is altered by any mechanical or chemical stress (strain, cracks, adsorption

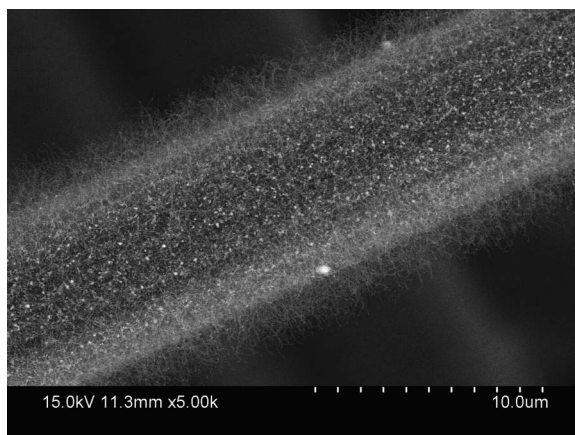


Figure 1. SEM micrograph of fuzzy fiber exhibiting low density and short length CNTs.

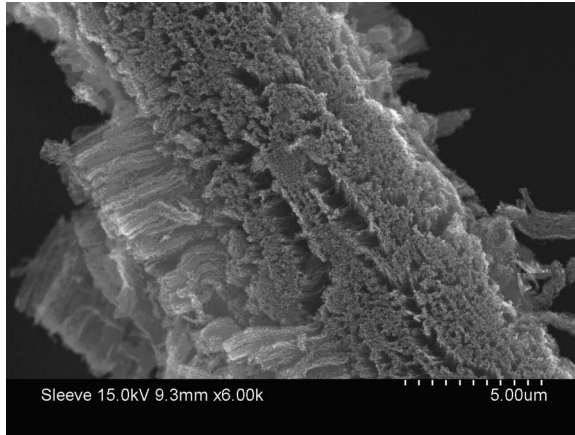


Figure 2. SEM micrograph of fuzzy fiber exhibiting high density and long length CNTs.

of molecular species, aging, etc.). The brittle nature of glass fibers might be suitable for the detection of crack initiation and propagation. The ability of the fuzzy fiber sensor to respond to chemical phenomena hints at its ability to provide a multifunctional role.

### 3. Experimental testing

A specially designed tension stage was built which provided the ability to perform tension tests on a single fuzzy fiber. The tension stage was constructed to hold the specimen horizontally so that the entire tension stage could be placed on an optical microscope, so that the test could be observed with the aid of magnification. The stage provides  $0.75\text{ }\mu\text{m}$  displacement resolution and a maximum load of 50 g. Figure 3 shows a detailed diagram of the specimen platens with test specimen in place.

The two halves of the specimen platen, where the fuzzy fiber is attached, are coated with epoxy to electrically insulate them from each other. A small drop of silver-filled epoxy was placed on top of the epoxy on each half of the sample plate. Before the silver-filled epoxy had cured, the fuzzy fiber was pushed into it, so that the fiber bridged the gap between the two halves of the specimen platen. A copper wire was also pushed into each drop of silver-filled epoxy, which provided the ability to measure the resistance of the fuzzy fiber before and during the test.

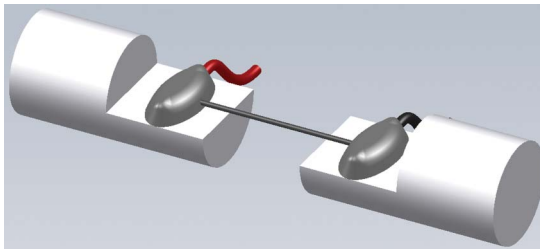


Figure 3. Diagram of tension stage showing fuzzy fiber mounted and instrumentation lead wires attached.

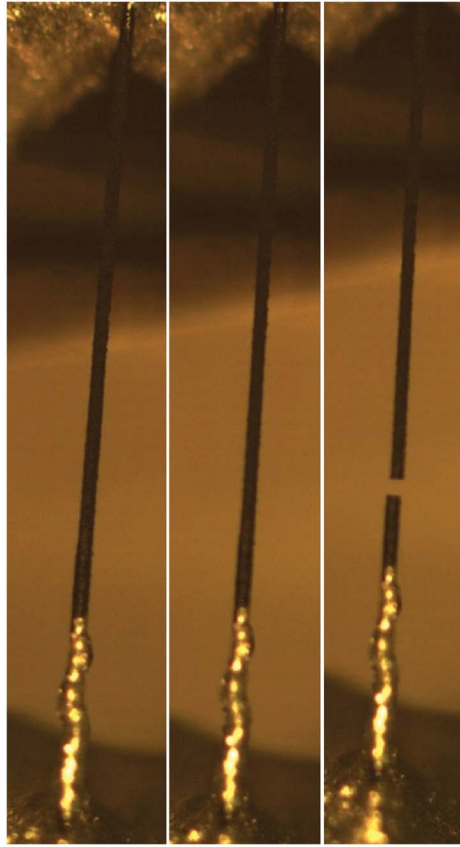


Figure 4. Time series of typical fuzzy fiber sensor under tension test.

The tension stage was placed in an optical microscope, which provided the ability to record a video of each test using the digital camera on the microscope. The microscope images were used to observe the test and validate it by ensuring that the fiber was not slipping in the epoxy and that the electrical resistance jumped to infinity at the instant the fiber failed, showing that the recorded strain and resistance values were correct. Figure 4 shows a time series of stills taken from a video of one test. The pictures show the initial position, the position during the test and the final position where the fiber failed. At this point, the load dropped to zero and the resistance went to infinity.

The stage was controlled using a custom Labview application, which provided the displacement drive signals and recorded the load data. The resistance data was recorded separately using a Keithley 2700 multimeter. Timestamps were used to synchronize the two data sets after each test was performed.

#### 4. Results and discussion

The tension tests provided load and displacement data, as well as the resistance data measured from the fuzzy fiber. Figure 5 shows the response of a low density fuzzy fiber sensor. The fuzzy fibers with a low density CNT coating exhibited a high resistance and were

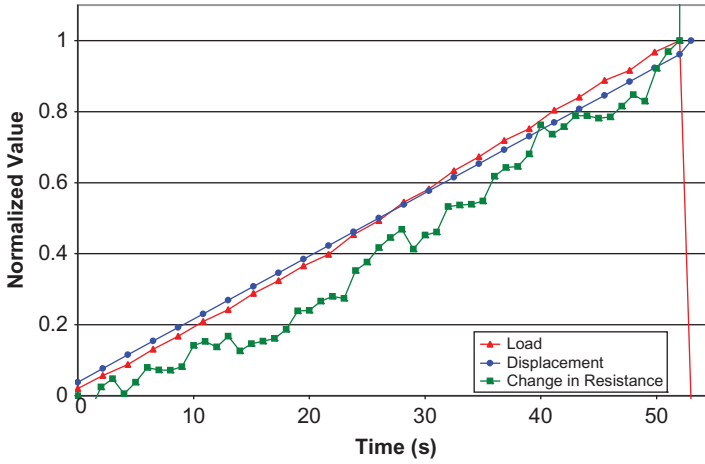


Figure 5. Load, displacement and sensor response data for a low density fuzzy fiber tension test.

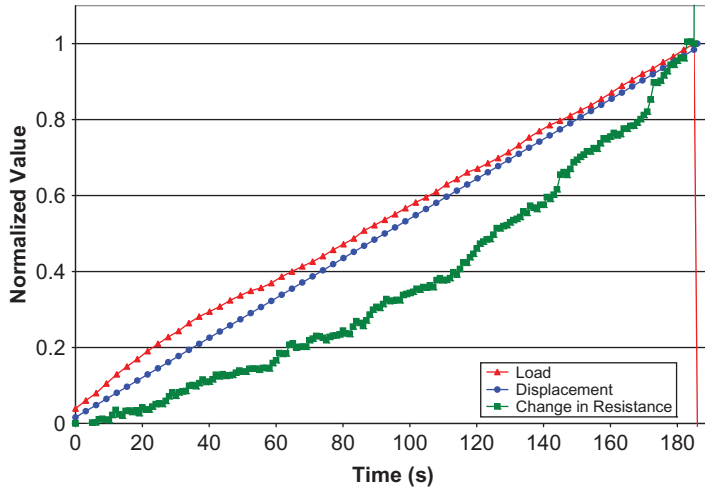


Figure 6. Load, displacement and sensor response data for a high density fuzzy fiber tension test.

therefore more susceptible to noise than the higher density sensors. The low density fibers are more sensitive but may not be useful for practical applications as they are easily damaged and their high resistance makes them more difficult to instrument. The higher density fuzzy fibers were easier to handle and more reliable in testing. Figure 6 shows the data from a typical tension test of a high density fuzzy fiber sensor. The response of the higher density sensor exhibits a similar response to the low density sensor; however, the data has less noise and the resistance change is not as pronounced.

The gage factor of the fuzzy fiber sensors is similar to that of commercially available metal foil strain gages. However, the large resistance and therefore large change in resistance of the sensors means that smaller strains can be detected due to the larger electrical response. This improves the signal to noise ratio and makes data acquisition more reliable. A common metal foil strain gage may exhibit a change in resistance of only several tens of

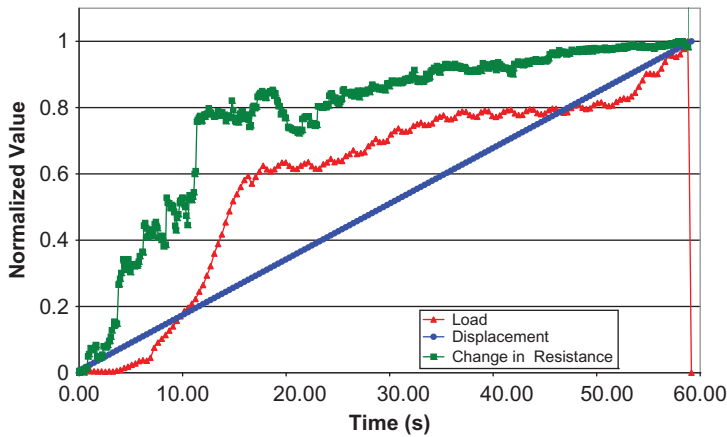


Figure 7. Load, displacement and sensor response data for a high density fuzzy fiber tension test which exhibited slippage in the fiber end connection.

ohms. The fuzzy fiber sensors, with similar gage factor, may exhibit a change of hundreds or even thousands of ohms.

Both sensor configurations demonstrate that the sensor has a significant response to strain. The response curves are not perfectly straight but it is believed that some slippage of the fiber occurred which may have led to this. Figure 7 shows a test with pronounced fiber slippage. The fiber initially picks up load quickly, and then the load plateaus as the fiber begins to pull out of the conductive epoxy mounting. The finite steps in displacement can be seen in the data where the sensor will pick up load, only to relax again. In this case, the sensor follows the true strain of the fuzzy fiber, rather than the apparent strain indicated by the displacement.

## 5. Conclusions

Fuzzy fibers have been shown to be effective strain sensors. Their high resistance provides increased electrical response over metallic foil strain gages and the small size and compatible materials of the fuzzy fiber sensors makes it easy to embed them within composite structures. Fuzzy fiber sensors comprised of a bundle of fuzzy fibers can be fabricated continuously at any practical length. These long lengths could provide wide area strain sensing, as well as detection of cracks, delamination or other structural failure. A spool of the fuzzy fiber sensor material could be laid into any composite part during layup and would be cured into the composite. A small conductive patch at each end of the fuzzy fiber would provide the electrical connections to an onboard monitoring system.

The fuzzy fiber strain sensor will find application in the aerospace, performance marine and wind energy markets, where the heavy use of composite materials dictates the need for SHM. Fuzzy fiber sensors allow engineers to assess the integrity of the structure in real time and repair or replace critical components which are showing signs of structural damage. Embedded sensors will reduce costs by increasing the service life of components and allowing maintenance procedures to be performed before catastrophic failure occurs.

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